DESIGN OF A SWITCHED–RELUCTANCE MOTOR DRIVE FOR ELECTRIC PROPULSION

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The Power Ratings of an Electric Motor for Electric Vehicles (Final Report for Task (a) only)

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Introduction

This report presents the methodology used to calculate the peak and continuous power ratings of a Switched Reluctance Motor (SRM) used for electric propulsion of an Electric Vehicle (EV).

The EV America Technical Specifications [1], the ANSI-IEEE Standard for Rotating Electrical Machinery for Rail and Road Vehicles [2], and the NEMA Standard for Motors and Generators [3] address the rating of electric motors used in EVs. The *EV America Technical Specifications* (effective 1997) lists the minimum specifications for an EV qualifying as an EV America "production-level" vehicle. It is considered that the vehicle is loaded with two 166-lb occupants and the battery is at a 50% state of charge. The listed minimum specifications are:

i. Minimum top speed of 70 mph.
ii. Acceleration time of 13.5 sec from 0 to 50 mph.
iii. Minimum sustainable speed of 55 mph on a 3% grade. Vehicle should be capable of maintaining a constant speed of 55 mph on a 3% grade for a minimum of 15 minutes.
iv. Minimum sustainable speed of 45 mph on a 6% grade.
v. Vehicle should be capable of ascending a 25% grade.

These specifications are used as a reference for sizing the SRM designed under this Office of Naval Research (ONR) Grant.

The *ANSI-IEEE Standard for Rotating Electrical Machinery for Rail and Road Vehicles* (IEEE Std 11-1980; upgraded in 1992) identifies the ratings to be stated when specifying an electric motor for road vehicles. These are briefly described below:

Continuous-power rating is the output power that the machine can sustain for an unlimited period of time. This rating is verified during testing by arranging the machine as in service with all those parts that would affect the temperature rise of the machine in place but without any ventilation produced by the motion of the vehicle itself. The test is continued until the temperature rise observed during the test attains a steady final value.

One-hour power rating is the output power that the machine can sustain for one hour starting cold. The observable one-hour temperature rise is the same as that one in the test for the continuous-power rating.

Short-time overload power rating is the output power that the machine can sustain for a specified time starting hot. This rating is verified by a temperature-rise test following the test for the continuous-power rating at the highest continuous current.

The *NEMA Standard for Motors and Generators* (NEMA MG1-1993) identifies the possible time ratings as 5 minutes, 15 minutes, 30 minutes, one hour and continuous operation.

For a particular electric propulsion application, the EV main specifications are the vehicle maximum mass (m_{ev}), maximum and rated speeds ($v_{ev,max}$ and $v_{ev,r}$), acceleration and deceleration times (t_a and t_d), maximum slope or gradient (α), rolling coefficient (k_r), EV frontal area (A_f), dragging coefficient (k_d), headwind speed (v_{hw}), wheel radius (r_w), gear box ratio and driving schedule(s). In turn, the rating of the EV electric motor (the SRM in this case) is determined from the EV main specifications.

The driving schedule data are given in the form of vehicle velocity at time instants equally spaced; we will consider the "Federal Urban and Highway Driving Schedules" (FUDS). In particular, we will use the following:

The *EPA (Environmental Protection Agency) Urban Dynamometer Driving Schedule (UDDS)* representing city driving conditions and used for light-duty vehicle testing (see Figure 1).

The FTP (Federal Test Procedure) composed of the UDDS followed by the first 505 seconds of the UDDS (see Figure 2).

The Highway Fuel Economy Driving Schedule (HWFET) representing highway driving conditions under 60 mph (see Figure 3).

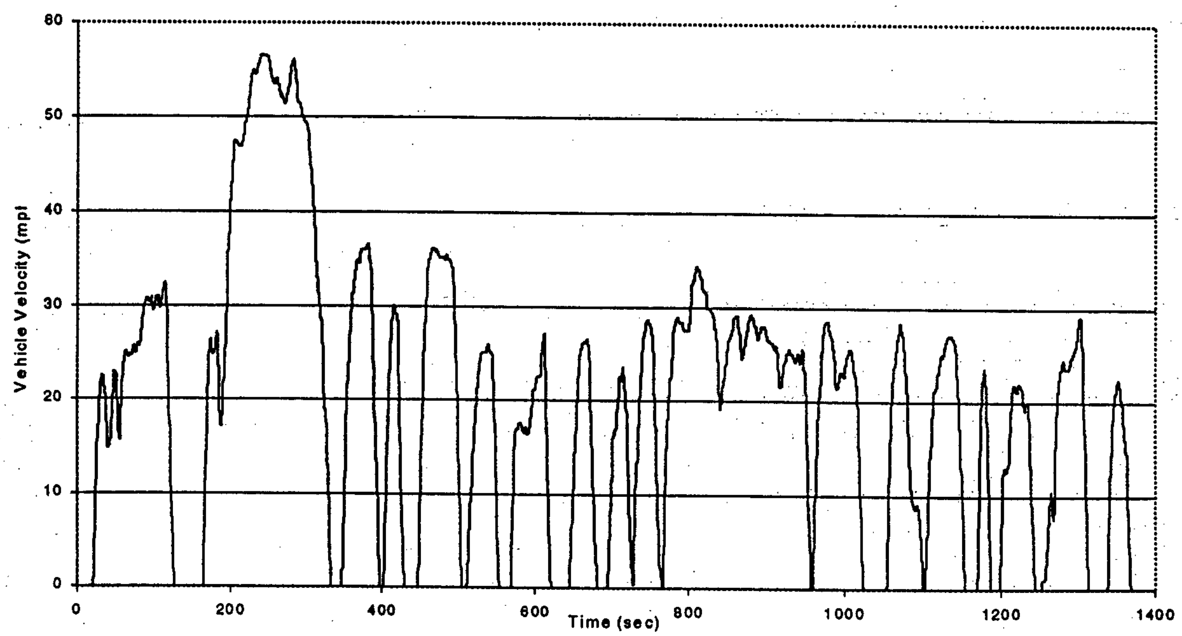

Figure 1 The UDDS is used for light duty vehicle testing.

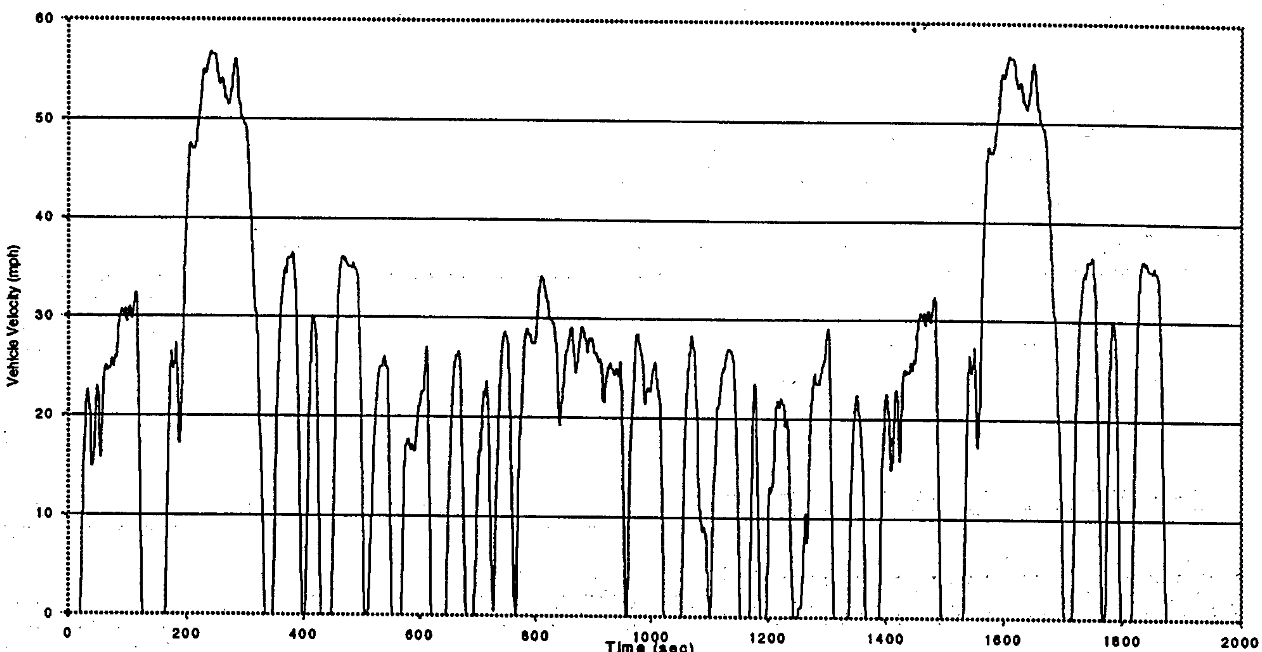

Figure 2 The FTP is composed of the UDDS followed by the first 505 seconds of the UDDS.

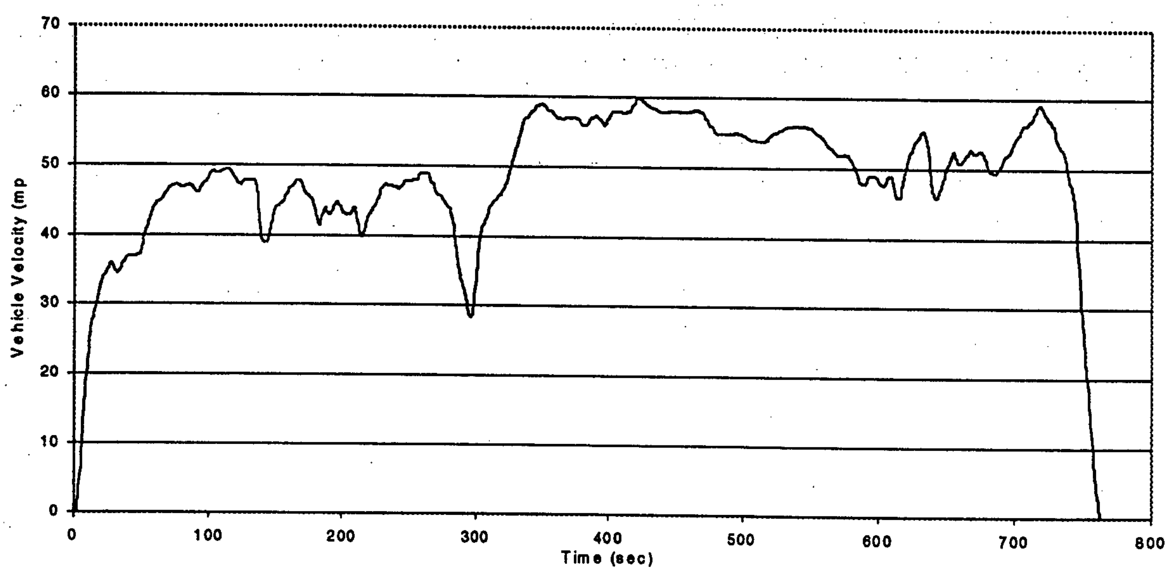

Figure 3 The HWFET represents highway driving conditions under 60 mph.

The remainder of this report addresses the calculation of the peak and continuous output power ratings for the following EV specifications:

Vehicle mass	= 1000 kg (GM Impact)
Mass considered in calculations	= 1172 kg (Vehicle with two 166-lb occupants)
Acceleration duty	= 0 to 50 mph in 13.5 sec
Maximum speed	= 70 mph
Rolling Coefficient	= 0.013
Aerodynamic Drag Coefficient	= 0.29
Gradient	= 0%, 3%, 6% and 25%
Frontal Area	= 2.13 m^2
Wind Velocity	= 5 mph.

Determination of the Power Ratings of the EV Electric Motor

The EV road-load force vs. vehicle speed characteristic (F_{ev} vs. v_{ev}) is calculated from the EV main specifications as follows [4]:

$$F_{ev}(v_{ev}) = k_r m_{ev} g + 0.5 a_d k_d A_f (v_{ev} + v_{hw})^2 + m_{ev} g \sin(\alpha) \tag{1}$$

where g is the acceleration due to gravity and a_d is the air density. Figure 4 shows the road-load and motor-drive forces as a function of the EV velocity with the shaded area indicating the available acceleration torque.

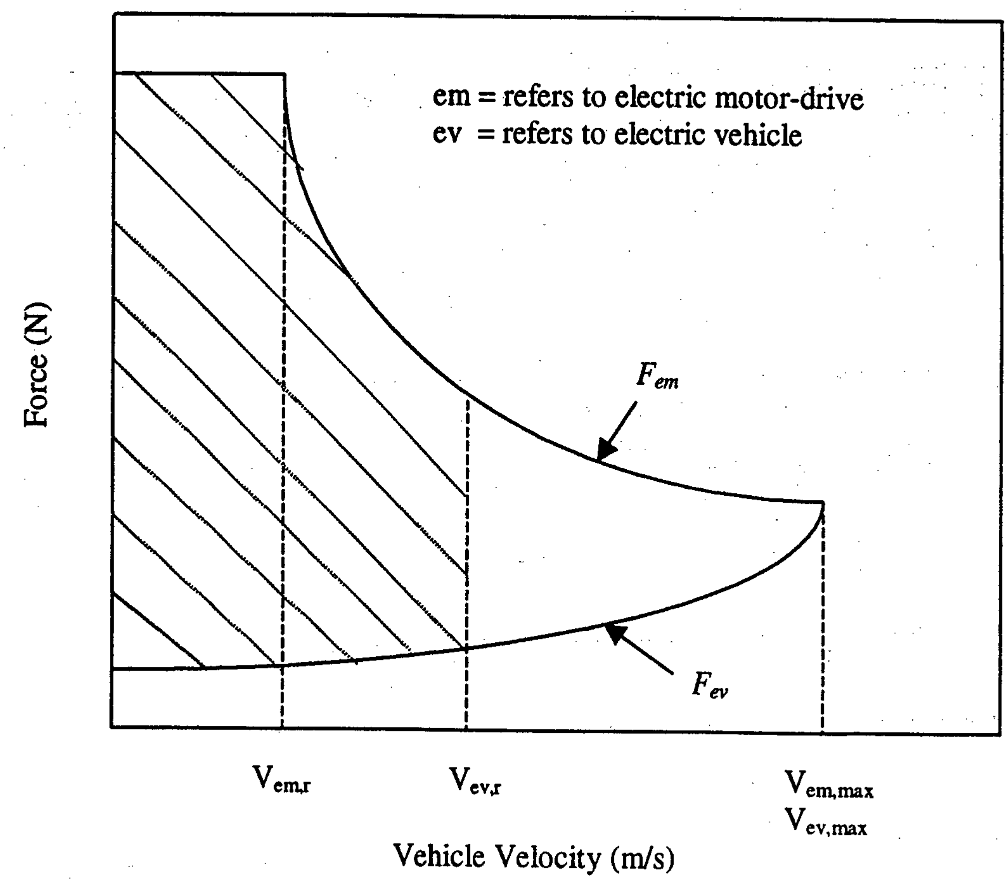

Figure 4 The road-load and motor-drive forces as function of vehicle velocity.

Using the road-load characteristic, the peak output power P_{emp} of the electric motor (in this case, the SRM) is determined by solving iteratively the following equation [4]:

$$t_a = k_m m_{ev} \left[\int_0^{v_{emr}} \frac{dv_{ev}}{\frac{P_{emp}}{v_{emr}} - F_{ev}(v_{ev})} + \int_{v_{emr}}^{v_{evr}} \frac{dv_{ev}}{\frac{P_{emp}}{v_{ev}} - F_{ev}(v_{ev})} \right] \tag{2}$$

Where k_m is the rotational inertia coefficient that accounts for the apparent increase in vehicle mass due to the onboard rotating mass (assumed to be 1.0 in this report) and in this case t_a is the specified acceleration time of 13.5 sec to attain the vehicle speed of 50 mph. Equation (2) is solved for P_{emp} for different values of $v_{em,max} / v_{em,r} = N_\omega$. This value of power is then compared with the power required at *(a)* the EV maximum speed; that is,

$$P_{em\max} = F_{ev}(v_{ev\max}) \times v_{ev\max} \qquad (3),$$

and the power P_{emg} required when the EV is moving at *(b)* 55 mph in a 3% gradient, *(c)* 45 mph in a 6% gradient and *(d)* the EV is ascending a 25% gradient. The value of P_{emp} is set equal to P_{emmax} or P_{emg} if any of these values is greater than the value of P_{emp} calculated from (2).

In [4], the peak power rating is called the rated power of the electric motor. However, for a complete specification of the electric motor, the peak and continuous power ratings should be identified separately. Also, the peak power should be corrected based on the requirements imposed by the driving schedules. This report illustrates a procedure to determine P_{emp} and P_{cont} by taking into account the driving schedules, the principles of operation of SRMs and assuming loss values at only one operating point. In the analysis, the total losses are equal to the sum of copper and total iron losses (i.e., $W_{SRM} = W_{cu} + W_{Fe}$). Rotational losses are not considered but they could be included as suggested in [2].

The continuous output power P_{cont} of the electric motor (the SRM in this case) must be determined by taking into account the thermal performance requirements imposed on the electric motor by the FUDS and cruising at the vehicle maximum velocity $v_{ev,max}$ (see the definition of continuous output power in the Introduction section). The losses generated during a specified operating condition determine the SRM temperature rise that should be within the limits specified in [2] for each class of insulation. Therefore, we need to identify that operating condition imposing the most severe thermal performance requirement on the SRM. This is done by determining the equivalent continuous rating $P_{cont,i}$ at rated speed for each operating condition. The SRM running at the considered operating condition generates the same losses as the SRM running at the equivalent continuous rating and rated speed. Finally, the operating condition resulting in the highest value of $P_{cont,i}$ determines the continuous rating of the motor P_{cont} (the motor should be tested at P_{cont} to verify its thermal performance).

Unfortunately, the SRM exact losses at any operating condition are not known since the SRM (or the electric motor) has yet to be designed. In order to relate known (or assumed) losses of the electric motor at a particular operating condition (e.g., $P_{em,max}$ and maximum speed) to any equivalent continuous rating $P_{cont,i}$ at rated speed, we need to define the ratio s between $P_{cont,i}$ and P_{emp} at the SRM rated speed:

$$s = P_{cont,i} / P_{emp} \tag{4}$$

For each specified operating condition (or driving schedule), this ratio s is calculated in an iterative manner using the Newton's algorithm to solve the following equation:

$$\boxed{s\,\{(1\text{-}c) + c\times f\} + s^{0.8} \times c \times (1\text{-}f) = (1\text{-}c) \times K_1 + c \times f \times K_{2e} + c \times (1\text{-}f) \times K_{2h}} \tag{5}$$

A first estimate of s is obtained ignoring the exponent 0.8. This equation (5) is obtained by equating the SRM total losses using:

- (10), (11) and (12) for the left-hand side, and
- (13), (14) and (15) for the right-hand side; these equations are given in the Appendix. Also, $P_1 = P_{cont,i}$, $P_2 = P_{emp}$, and $\omega_1 = \omega_2$.

The non-dimensional coefficients f, c, K_1, K_{2e} and K_{2h} are given as follows:

* The equivalent copper-loss coefficient K_1:

$$K_1 = \frac{1}{N}\frac{v_{emr}}{P_{emp}}\sum_{i=1}^{N}\frac{P_{di}}{v_{ev,i}} \tag{6}$$

* The equivalent eddy-current-loss coefficient K_{2e}:

$$K_{2e} = \frac{1}{N}\frac{1}{P_{emp}v_{emr}}\sum_{i=1}^{N}P_{di}v_{ev,i} \tag{7}$$

* The equivalent hysterisis-loss coefficient K_{2h}:

$$K_{2h} = \frac{1}{N}\frac{1}{P_{emp}^{0.8}v_{emr}^{0.2}}\sum_{i=1}^{N}C_i \tag{8}$$

With

$$C_i = P_{di}^{0.8}v_{ev,i}^{0.2} \qquad \text{for } v_{ev,i} <= v_{emr}$$

or

$$C_i = P_{di}^{0.8}v_{ev,i}^{0.2} \times \sqrt{\frac{v_{emr}}{v_{ev,i}}} \qquad \text{for } v_{ev,i} > v_{emr}$$

The power P_{di} in the above equations is the power required from the electric motor at the center of each time interval in a driving schedule is calculated by assuming a linear velocity profile between any two consecutive time instants (see Figure 5). This power is given by:

$$\boxed{P_{di} = (F_a + F_{ev}) \times \frac{v_{ev,i-1} + v_{ev,i}}{2}} \tag{9}$$

Where the required force components are determined as follows:

1) F_a is the acceleration component to accelerate the vehicle from velocity $v_{ev,i-1}$ at time instant t_{i-1} to velocity $v_{ev,i}$ at time instant t_i. This force is given by:

$$F_a = k_m m_{ev} \frac{v_{ev,i} - v_{ev,i-1}}{t_i - t_{i-1}}$$

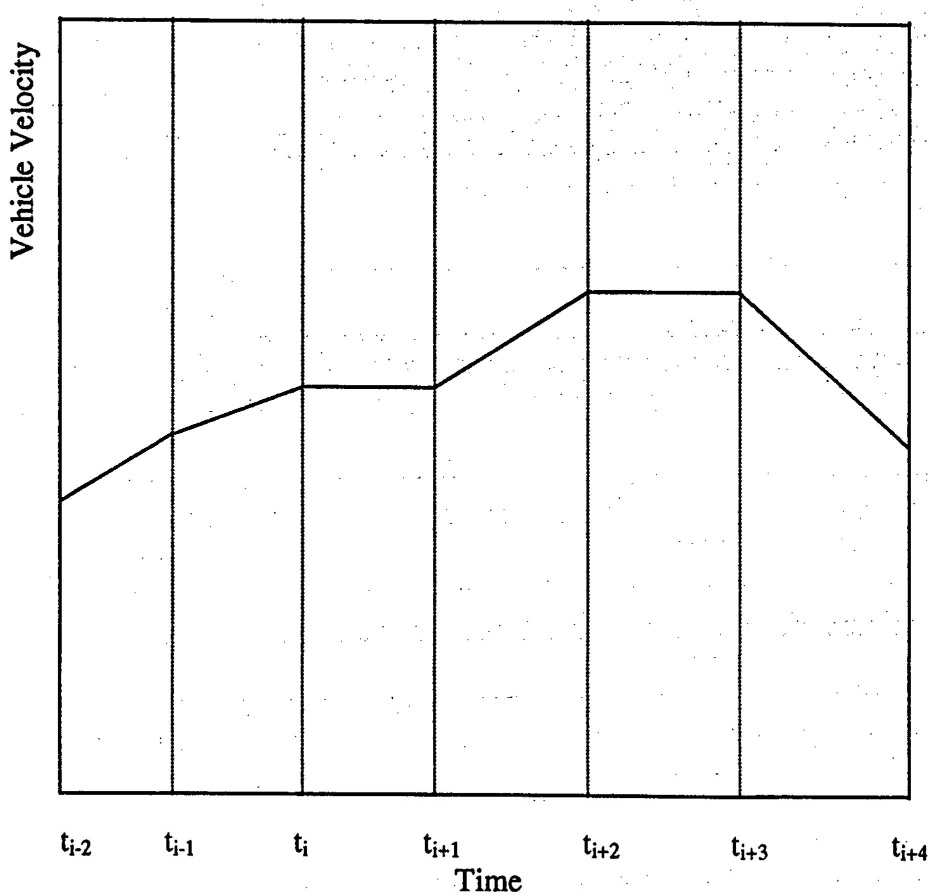

Figure 5 A portion of a driving schedule showing the assumption of a linear velocity profile between any two instants.

2) F_{ev} is the force required for overcoming the road load. This force is calculated using (1) for a velocity corresponding to the center of the considered time interval.

A negative value of P_{di} means that the vehicle requires braking power; that is, the electric motor participates in regenerative braking. In this case, the calculated P_{di} is inverted in sign for only the purpose of estimating the motor losses.

The total force during acceleration $(F_a + F_{ev})$ must be checked if it is less than or equal to the peak capability of the SRM based on the value of P_{emp} calculated earlier. If it is not the case, the peak power P_{emp} of the SRM has to be increased. In this analysis, we assumed that any additional force required during deceleration is provided by a mechanical braking system.

N represents the number of time instants in the considered driving schedule. The Appendix shows the derivation of (6), (7) and (8).

The coefficient f represents the ratio between the eddy current and total iron losses (i.e., $f = W_{ep} / W_{Fep}$) and the coefficient c represents the ratio between the total iron loss and total losses of the electric motor (i.e., $c = W_{Fep} / W_{SRMp}$). These coefficients correspond to peak output power P_{emp} and any arbitrary speed (we selected the SRM rated speed). We have assumed values for these two coefficients based on SRM designs presented in the literature [5-6]. The accuracy of the calculated or estimated P_{cont} depends on the "closeness" between the assumed values and those of the designed and built SRM.

Software Program "Ecar"

The software program "Ecar" was written in Visual C++ using Microsoft Developer Studio to implement the ideas set forth in this section. The input data, entered in an interactive manner, are:

1) Maximum velocity (mph)
2) Rated velocity (mph)
3) Acceleration time (sec)
4) Vehicle mass (kg)
5) Considered maximum speed ratio N_ω (i.e., Maximum/rated velocity of the motor drive)
6) Dragging coefficient
7) Rolling coefficient
8) Maximum gradient
9) Wind velocity
10) Air density (kg/m^3)
11) Acceleration due to gravity (m/sec^2)
12) EV frontal area (m^2)

Table 1 lists the peak output power of the motor drive P_{emp} calculated by "Ecar" along with those calculated in [4] for different speed ratios ($\omega_{em,max}$ / $\omega_{em,r}$) for the following EV specifications (that are used in [4]):

Maximum Velocity	=	100 mph
Rated Velocity	=	60 mph
Acceleration time	=	10 sec
Rolling Coefficient	=	0.013
Aerodynamic Drag Coefficient	=	0.29
Gradient	=	0.0
Frontal Area	=	2.13 m^2
Wind Velocity	=	0 mph
Vehicle mass	=	1450 kg

Excellent agreement is achieved for all considered speed ratios.

Table 1. Comparison of Ecar's results with those results in [4].

Speed Ratio	Peak Power Rating from [4] (kW)	Peak Power Rating from the Program (kW)
2:1	95	95
3:1	74	75
4:1	67	67
5:1	64	64
6:1	62	63

Calculation of the SRM Power Ratings

The EV specifications for the ONR project given in the Introduction are repeated here for completeness:

Vehicle mass	=	1000 kg (GM Impact)
Mass considered in calculations	=	1172 kg (Vehicle with two 166-lb occupants)
Acceleration duty	=	0 to 50 mph in 13.5 sec
Maximum speed	=	70 mph
Rolling Coefficient	=	0.013
Aerodynamic Drag Coefficient	=	0.29
Gradient	=	0%, 3%, 6% and 25%
Frontal Area	=	2.13 m^2
Wind Velocity	=	5 mph.

It is assumed that the maximum rotor speed of the SRM is five times the rated speed; hence, a speed ratio of 5:1 [4].

SRM peak output power rating

Using "Ecar", we calculated the following power requirements:

(1) Accelerating from 0 to 50 mph in 13.5 sec = 28 kW
(2) Ascending a 25% gradient (speed of 20 mph) = 28 kW
(3) Maintaining 55 mph in a 3% gradient = 20 kW
(4) Maintaining 45 mph in a 6% gradient = 21 kW
(5) Cruising at the maximum vehicle velocity = 19 kW at the maximum motor speed

Thus, peak output power rating P_{emp} of the SRM is specified as 28 kW.

Continuous power rating

The values of K_1, K_{2e}, K_{2h} and s were determined using the driving schedules FTP and HWFET as well as the power requirement at the maximum vehicle velocity of 70 mph. The results are illustrated below:

Condition	K_1 (6)	K_{2e} (7)	K_{2h} (8)	s (5)	$P_{cont,i}$ (4)
FTP	0.12136	0.38127	0.25296	0.171677	5
HWFET	0.10313	1.22187	0.45482	0.324122	9
Cruising at maximum vehicle speed	0.13333	3.3333	0.44610	0.626630	18

Values of $f = 0.333$ and $c = 0.4$ (considered typical for a SRM) were assumed. "Ecar" solves (5). Thus, the continuous output power P_{cont} of the SRM is specified as 18 kW at the rated speed of motor. This corresponds to a P_{emmax} of 19 kW at the maximum speed.

Assuming a safety factor of 1.2, the output power ratings of the SRM to be designed under this ONR Grant are:

Peak power = 35 kW at and above the rated speed of the SRM.
Continuous power = 23 kW at the maximum speed of the SRM.

Figure 7 shows the variation of motor losses with vehicle velocity when the motor is developing the power required to overcome the specified road load. Each loss component is normalized (in per-unit) with respect to its corresponding loss at the peak output power and rated speed. The total losses are plotted using the assumed values of f and c. It is clear from Figure 7 that the losses are the highest when the vehicle is cruising at the maximum vehicle speed of 70 mph.

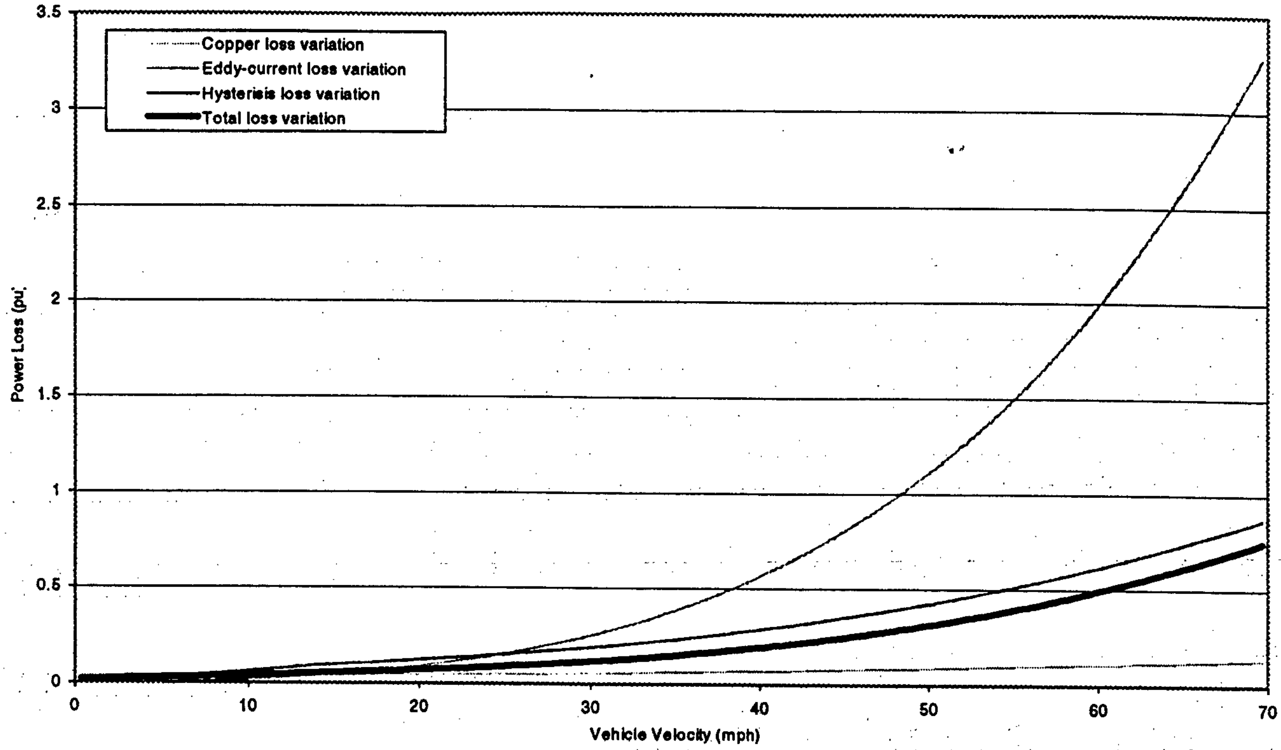

Figure 7 Variation of loss components and total losses with vehicle velocity.

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Appendix

Estimation of Power Losses in a SRM

Applying a current pulse to a phase winding where the inductance has a positive slope controls the SRM. Assuming an ideal rectangular current pulse, Figure A.1 shows the current waveform, the inductance variation of the torque producing phase and the stator-pole flux waveform. The flux waveforms in other regions of the magnetic circuit are related to the flux waveform in the stator pole as shown in [7]. The current pulse either occupies the full feasible region for torque production (i.e., from rotor angle θ_1 to rotor angle θ_2) or the dwell angle is changed so that it occupies a smaller region. This is illustrated by the current pulse I' in Figure A.1. For the same average torque, the amplitude I' has to be greater than that of I and the two currents are related as follows:

$$I'^2(\theta_{off}-\theta_1) = I^2(\theta_2-\theta_1).$$

One can get an idea of the meaning of $(\theta_2 - \theta_1)$ by noting that it is equal to 30° for the 6/4 SRM. So the number of current pulses per revolutions (4) times the number of phases (3) times $[\theta_2 - \theta_1]$ (30°) is equal to 360°; the angle corresponding to one full revolution of the rotor.

The relationships relating the variations of power losses as function of output power and motor speed are necessary in order to determine the continuous power rating of the SRM. Unfortunately, it is not possible to determine the exact variations unless the SRM is already designed; therefore, an estimation of the loss variations will be used instead.

The following assumptions are made in estimating the variations of power losses with the output power and speed of the SRM:

1) Effects of magnetic saturation are neglected.

2) The formulation relating the power output and speed to the losses is only valid as long as the current pulse is restricted to the region $(\theta_2-\theta_1)$ or, in general, to the torque producing zone (see Figure A.1). In an actual case, the decaying trailing edge of the current pulse will be present in the region immediately after $(\theta_2-\theta_1)$; this decaying-current pulse is neglected.

3) It is assumed that the current pulse applied to the winding always has a rectangular-wave shape. This is only true at low-speed operation of the SRM. For high-speed operation, the current pulse applied is "peaky". Such a waveform will not lead to any additional error in the estimation of copper losses as long as its rms value is identical to that of the rectangular-wave shape case. The equations for eddy-current loss and hysterisis loss are only valid as long as the current waveform is flat-topped (i.e., constant amplitude). The error in the estimated losses will not be high as long as the periods when (di/dt) is large are small [6].

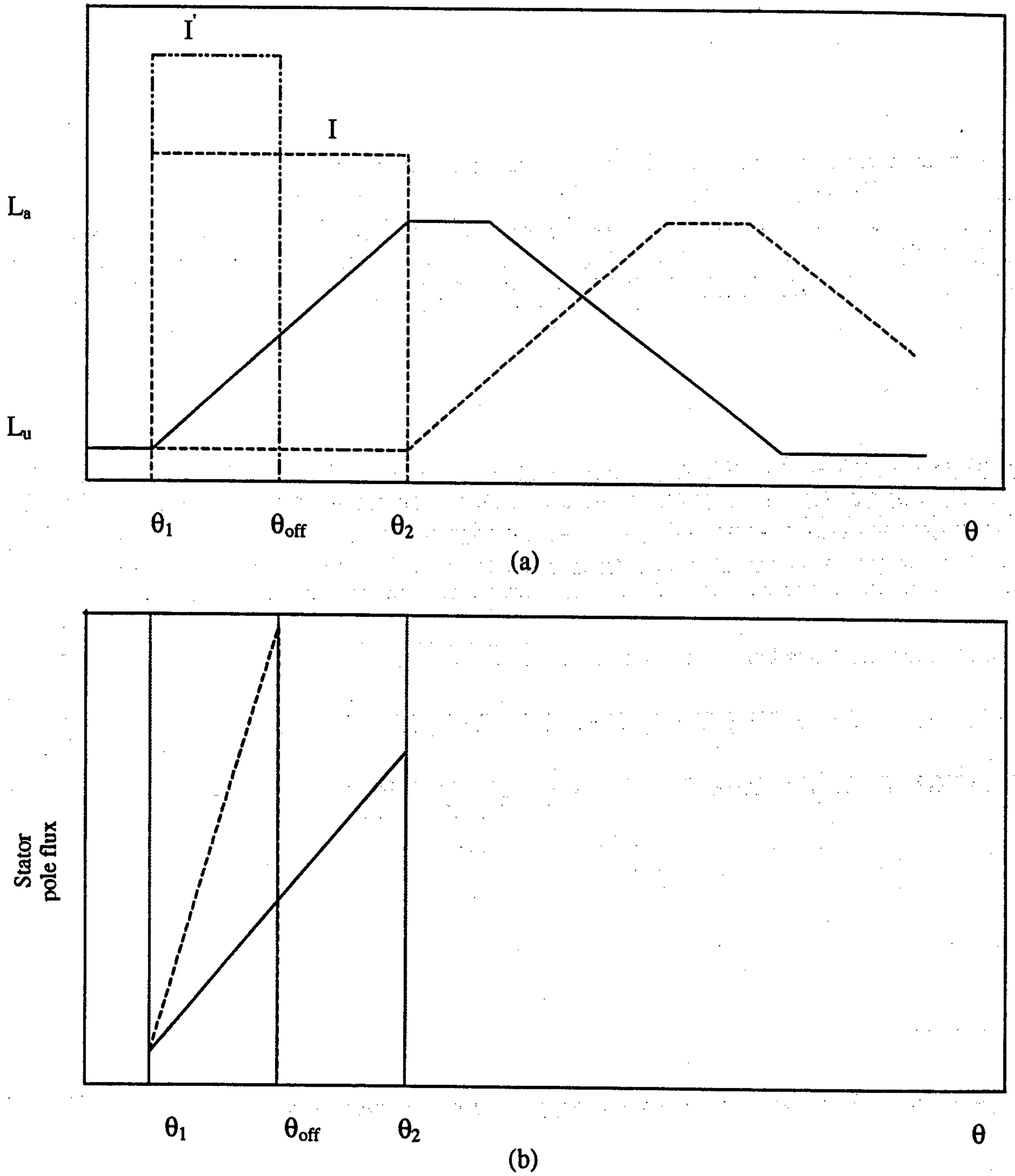

Figure A.1 (a) The ideal phase-inductance and phase current. (b) The stator-pole flux waveform. The effect of reducing dwell-angle on the current and the stator-pole flux is illustrated in (b).

4) The equation for the copper loss is not valid for zero motor speed.

5) As per the Steinmetz equation, the hysterisis loss is determined by

$$W_h \propto B_{\max}^{n}\ \omega,$$

where Steinmetz found that "n" has a value of 1.6 for a wide variety of materials [8]. For the new ferromagnetic alloys, "n" may vary from 1.5 to 2.5. In fact, "n" is not a constant except for a limited range. By taking "n" constant, we are assuming that the shape of the hysterisis curve remains unchanged. This assumption is necessary to be able to simplify the formulation for the hysterisis loss in the absence of knowledge for B_m. Therefore, we decided to use the following hysterisis-loss equation:

$$W_h \propto B_{\max}^{1.6}\ \omega.$$

From the driving schedules and the EV main specifications, we know the output power and speed of the motor drive at various time instants. In order to calculate the continuous power rating of the SRM, we will relate the losses in the SRM at a known output power and speed to the output powers and speeds in the considered driving schedule. The following analysis illustrates this procedure.

Variation of the copper loss

Consider a SRM producing torque T_1 at speed ω_1 and torque T_2 at speed ω_2. Since the SRM torque varies as a function of the square of the current under the assumption of magnetic linearity, the copper loss is then directly proportional to the output torque. Thus,

$$\frac{W_{cu1}}{W_{cu2}} = \frac{T_1}{T_2}$$

Since

$$T = \frac{P}{\omega}$$

The copper losses at two different output powers and speeds are related as follows:

$$\boxed{\frac{W_{cu1}}{W_{cu2}} = \frac{P_1}{P_2}\frac{\omega_2}{\omega_1}} \qquad (10)$$

Now, consider that the torque required at a particular speed is produced by applying a current pulse throughout the angle range $(\theta_2 - \theta_1)$ and the same torque is produced by the smaller angle range $(\theta_{off} - \theta_1)$, the copper loss is then given by:

* Current pulse throughout the angle range (θ_2 - θ_1) with amplitude I:

$$W_{cu1} \propto I^2$$

* Current pulse with reduced dwell angle $(\theta_{off} - \theta_1)$ and amplitude I':

$$W_{cu2} \propto I'^2 \frac{(\theta_{off} - \theta_1)}{(\theta_2 - \theta_1)} \propto I^2$$

Thus, the length of the dwell angle does not affect the copper loss.

Variation of the eddy-current loss

The flux in the stator pole is proportional to the phase flux linkages that may be expressed as follows:

$$\lambda \propto L_u I + K(\theta - \theta_1)I$$

where

$$K = \frac{L_a - L_u}{\theta_2 - \theta_1}$$

where L_a is the aligned inductance and L_u is the unaligned inductance.

Also, the flux density B is proportional to the flux per turn and also to the flux linkage λ. Then, the rate of change of the flux density can be written as follows:

$$\frac{dB}{dt} \propto \frac{d\lambda}{dt} \propto \frac{d(L_u I + KI(\theta - \theta_1)}{dt}$$

$$\therefore \frac{dB}{dt} \propto KI\omega$$

The eddy-current losses can be approximated by:

$$W_e \propto \left(\frac{dB}{dt}\right)^2$$

$$\therefore W_e \propto K^2 I^2 \omega^2$$

Now, assume that a SRM develops torque T_1 at speed ω_1 and torque T_2 at speed ω_2, then we can write:

$$\boxed{\frac{W_{e1}}{W_{e2}} = \frac{P_1}{P_2}\frac{\omega_2}{\omega_1}\left(\frac{\omega_1}{\omega_2}\right)^2 = \frac{P_1}{P_2}\frac{\omega_1}{\omega_2}} \tag{11}$$

It can be shown that the eddy-current loss W_e remains unchanged if the same torque at a particular speed is produced by either applying a current pulse throughout the angle range $(\theta_2 - \theta_1)$ or by using a reduced dwell-angle since $W_e \propto K^2 I^2 \omega^2$.

Variation of the hysterisis loss

The hysterisis loss is given by,

$$W_h \propto B_{\max}^{1.6}\omega$$

Since

$$B_{\max} \propto \phi_{\max} \propto \lambda_{\max} = (L_a + L_u)I$$

$$\frac{W_{h1}}{W_{h2}} = \left(\frac{I_1}{I_2}\right)^{1.6}\frac{\omega_1}{\omega_2} = \left(\sqrt{\frac{\omega_2 P_1}{\omega_1 P_2}}\right)^{1.6}\frac{\omega_1}{\omega_2}$$

$$\boxed{\frac{W_{h1}}{W_{h2}} = \left(\frac{P_1}{P_2}\right)^{0.8}\left(\frac{\omega_1}{\omega_2}\right)^{0.2}} \tag{12}$$

If the same torque at a particular speed is developed by reducing the dwell angle, then:

$$B'_{\max} \propto L_u I' + K(\theta_{off} - \theta_1)I'$$

Above rated speed, the dwell-angle is changed such that

$$\frac{\theta_{off} - \theta_1}{\theta_2 - \theta_1} = \frac{\omega_{rated}}{\omega}$$

Hence,

$$\boxed{\frac{W_h'}{W_h} \propto \sqrt{\frac{\omega_{rated}}{\omega}}}$$

Based on the above formulations, the efficiency contours have been determined and plotted in Figure A.2 for a SRM having an efficiency of 85% at peak output power and rated speed, $f = 0.333$ and $c = 0.4$. These contours are similar in shape to those given in [9].

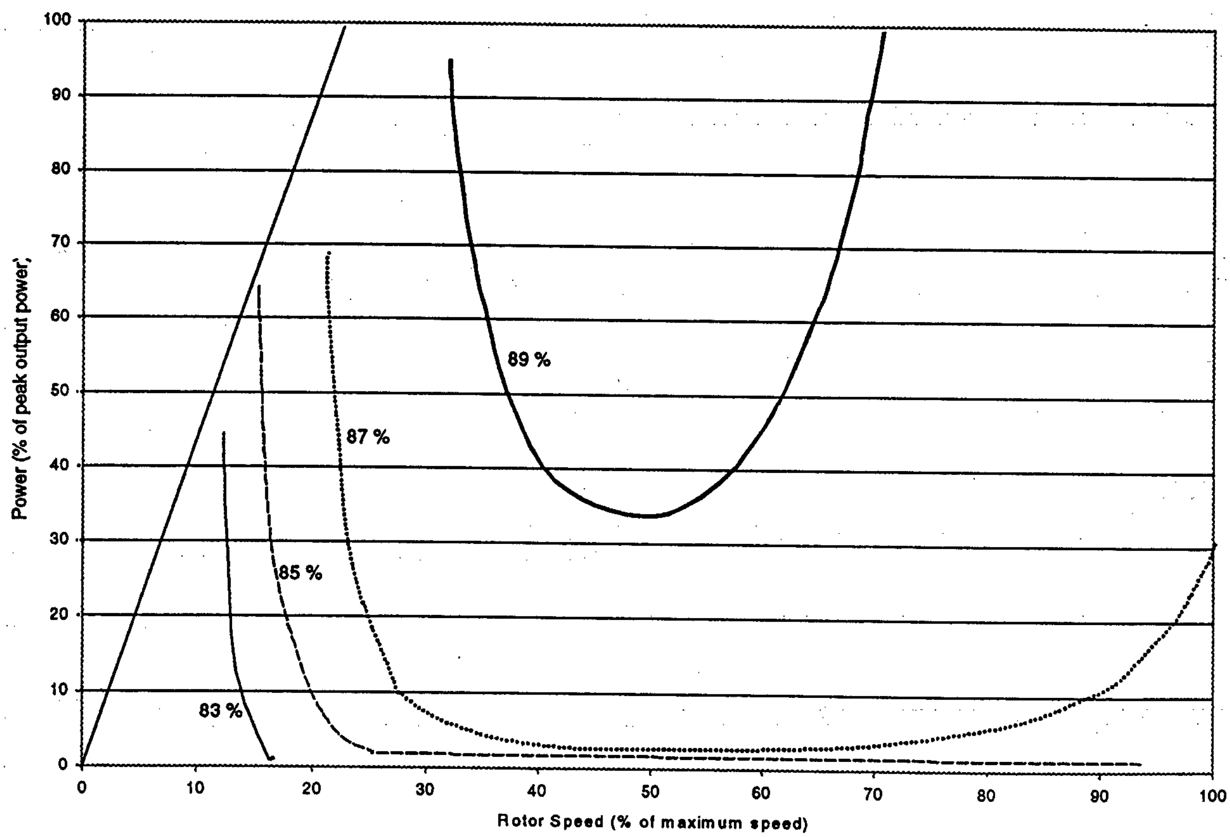

Figure A.2 Efficiency contours of a SRM.

Derivation of the coefficients K_1, K_{2e}, K_{2h}

Let us assume that we know the copper loss W_{cup}, the hysterisis loss W_{hp} and the eddy-current loss W_{ep} of the motor at the peak output power P_{emp} and rated speed ω_{emr}.

Knowing the output power P_{di} required from the motor drive at the different time instants of a driving schedule, the average copper loss over the entire driving schedule, which determines the temperature rise of the electric motor, can be calculated using (10) as follows:

$$W_{cu} = \frac{W_{cup}}{N} \times \frac{\omega_{emr}}{P_{emp}} \times \left(\frac{P_{d1}}{\omega_1} + \frac{P_{d2}}{\omega_2} + \ldots\ldots + \frac{P_{dN}}{\omega_N} \right)$$

$$\therefore \quad W_{cu} = K_1 \times W_{cup} \tag{13}$$

Where

$$\boxed{K_1 = \frac{1}{N} \times \frac{\omega_{emr}}{P_{emp}} \times \left(\frac{P_{d1}}{\omega_1} + \frac{P_{d2}}{\omega_2} + \ldots\ldots + \frac{P_{dN}}{\omega_N} \right)}$$

Using (11), the average eddy-current loss over the entire driving schedule is given by:

$$W_e = \frac{W_{ep}}{N} \times \frac{1}{P_{emp}\omega_{emr}} \times \left(P_{d1}\omega_1 + P_{d2}\omega_2 + \ldots\ldots + P_{dN}\omega_N \right)$$

$$\therefore \quad W_e = K_{2e} \times W_{ep} \tag{14}$$

Where

$$\boxed{K_{2e} = \frac{1}{N} \times \frac{1}{P_{emp}\omega_{emr}} \times \left(P_{d1}\omega_1 + P_{d2}\omega_2 + \ldots\ldots + P_{dN}\omega_N \right)}$$

Using (12), the average hysterisis loss over the entire driving schedule is given by:

$$W_h = \frac{W_{hp}}{N} \times \frac{1}{P_{emp}^{0.8}\omega_{emr}^{0.2}} \times (C_1 + C_2 + \ldots + C_N)$$

$$\therefore \quad W_h = K_{2h} \times W_{hp} \tag{15}$$

Where

$$\boxed{K_{2h} = \frac{1}{N} \times \frac{1}{P_{emp}^{0.8} \omega_{emr}^{0.2}} \times (C_1 + C_2 + ... + C_N)}$$

and

$$C_i = P_{di}^{0.8} \omega_i^{0.2} \qquad \text{for } \omega_{i <=} \omega_{emr}$$

$$C_i = P_{di}^{0.8} \omega_i^{0.2} \times \sqrt{\frac{\omega_{emr}}{\omega_i}} \qquad \text{for } \omega_{i >} \omega_{emr}$$

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This report presents the methodology used to calculate the peak and continuous power ratings of a Switched Reluctance Motor (SRM) used for electric propulsion of an Electric Vehicle (EV). A procedure is given to calculate the peak and continuous power ratings by taking into account the driving schedules, the principles of operation of SRMs and assuming loss values at only one operating point.

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